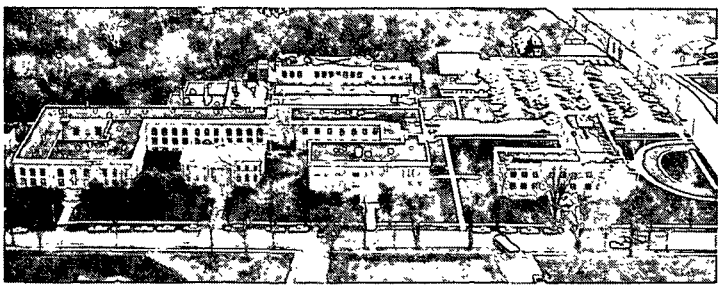

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S. W. BURTON AND C. H. SPRAGUE

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S. W. Burton and C. H. Sprague

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THE INSTANTANEOUS MEASUREMENT OF DENSITY PROFILE DEVELOPMENT DURING WEB CONSOLIDATION

S. W. BURTON
RESEARCH SCIENTIST
UNION CAMP CORPORATION
PRINCETON, NJ

AND

C. H. SPRAGUE
DIRECTOR, ENGINEERING DIVISION
THE INSTITUTE OF PAPER CHEMISTRY
APPLETON, WISCONSIN 54912 U.S.A.

ABSTRACT

A new method for measuring the instantaneous z-direction density profile of fiber mats during consolidation is described. The measurement technique involves the tracking of special open-mesh targets embedded in the sheet at various levels, by a noncontact displacement measuring system mounted in the bottom press platen. Factors of critical importance to successful measurements are discussed. Density profile measurements made under wet pressing and impulse drying conditions are presented to demonstrate the applicability of the measurement technique.

KEYWORDS: Density, Impulse Drying, Measurement, Pressing, Z-Direction

INTRODUCTION

During the pressing operation on a paper machine, water removal is accomplished by mechanically squeezing water from the sheet. It is the primary purpose of the press section to maximize water removal while simultaneously creating the density potential required for developing desirable paper properties. Over the years, press designs have been altered in an effort to improve the performance of the operation. To understand the fundamental limitations which restrict further increases in water removal for pressing as well as other consolidation processes, it is important to first understand the dynamics of water removal. Since dewatering forces also densify the sheet, measurement of the density distribution as it is created would provide a means for studying these dynamic forces. This was the premise for developing the density measurement technique described in this paper. The method involves the direct measurement of the z-direction density profile as it develops during compression.

Several investigators (1-4) have studied the dynamic compression of fiber mats. The experimental studies have included the instantaneous measurement of applied pressure, hydraulic pressure, and total sheet thickness as a means for investigation. Up to this point, however, there have been no reports on the instantaneous measurement of density profile development.

MacGregor (5) speculated on how nonuniform density development may occur during pressing through a process he calls stratification. This process is defined as the development of a z-direction density profile resulting from the redistribution of sheet fiber and filler caused by fluid shear forces. MacGregor described the expected compression response of an idealized sheet divided into twelve regions of equal basis weight. By combining the experimental results of Chang (1) with fundamental concepts of flow in compressible porous media, MacGregor was able to describe in detail the probable compression response of the individual fiber regions to the mechanical and fluid shear forces that occur during pressing. In contrast, the results reported in this paper are direct measurements of the instantaneous compression response of up to three individual sheet regions from which information on dewatering and densifying mechanisms are derived.

The method to be described was originally developed for determining the instantaneous z-direction density profile in paper sheets during impulse drying (6). However, it has also been utilized for investigating densification during wet pressing. In fact, it may be applied to almost any consolidation process which can be simulated by compression between parallel plates. Experimental results from both wet pressing and impulse drying will be presented to demonstrate the applicability of the measurement technique. Since the density profile measurement requires handsheets with special open-mesh targets embedded at various levels, a method for handsheet preparation will also be described.

EXPERIMENTAL

Apparatus

Figure 1 is a schematic of the experimental heads used in the density profile measurement. The upper head is used as the pressing surface and can be electrically heated up to 500 C for compression studies at elevated temperatures. The lower head is usually fixed and supports the sheet as the upper head compresses it. Water is expressed from the wet sheet into a 1.6-mm thick ceramic flow receiver which has an average pore size of 40 μm. Use of the rigid ceramic limits the press nip to one compressible material and contributes to a uniform pressure distribution

on the sheet. A vented drilled brass plate (2.4 mm diameter holes) under the ceramic accepts excess water. Both heads have a diameter of 100 mm.

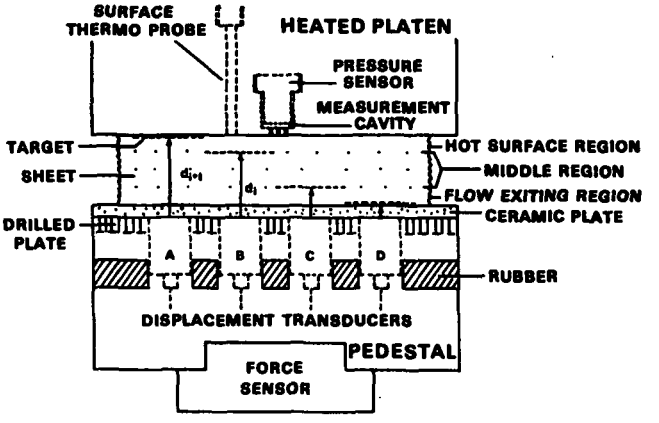

Figure 1. Schematic of the press platens used in the density profile determination during wet pressing and impulse drying.

The heads depicted in Fig. 1 have, in most cases, been used on a simple wet pressing device, commonly known as a Wahren-Zotterman falling-weight press nip simulator (7). The simulator has been shown in a comparative study to accurately duplicate press nip impulse characteristics (8). Nip residence times ranging from 3 to 25 milliseconds have been achieved with the apparatus. A limited number of tests have also been performed on an electrohydraulic testing system. This system, while much more versatile than the Wahren-Zotterman simulator, is limited to pressure pulses beyond 10 milliseconds duration.

Instrumentation

The lower head is instrumented with a force transducer (PCB Piezotronics, Inc.) to measure the force applied by the upper head, and four displacement transducers to provide data necessary for the determination of the sheet density profile. The transducers are rigidly mounted and epoxied to the lower head to prevent movement during testing. A Tracor Northern TN-1710 system is used for data acquisition.

The displacement transducers are of the eddy current type manufactured by Kaman Instrumentation Corp. and are used to track the motion of targets during compression. They have a measuring range of 4.0 mm with resolution of 0.01% of full scale calibration. Accurate calibration over a measurement span of 1.25 mm is done with a special micrometer, accurate to within 6.35 μm, to which a sample target is attached. The transducers are calibrated while rigidly mounted in the lower head, prior to each set of compression tests (5-15 tests/set).

Figure 2 is a typical linear calibration curve of displacement versus voltage with a correlation coefficient of 0.99999.

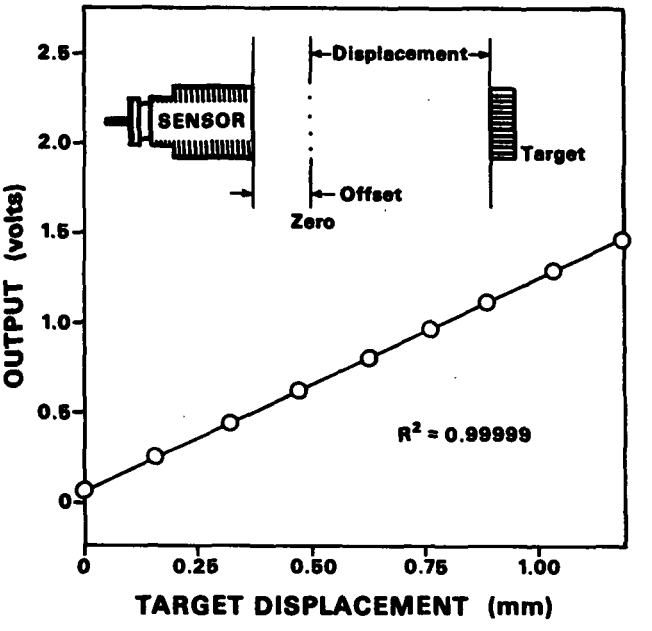

Figure 2. Typical linear calibration curve of displacement vs. voltage.

Dynamic Density Profile Determination

The density profile is obtained by dynamically measuring the thickness of specific regions of known basis weights in the sheet. The targets used in the method are embedded in the sheet at various levels during sheet formation (see Fig. 1) and are thin relative to total sheet thickness. During consolidation, the targets move with the surrounding fiber network in response to dewatering and densifying forces. The displacements of the targets are recorded from the transducers mounted in the lower head. The instantaneous density of a region is then calculated from adjacent target separation and region basis weight, as indicated in Fig. 1, such that:

$$\rho_i = W_i/(d_{i+1} - d_i)$$

where,

ρ_i = apparent density of the ith web region (g/cm^3)

W_i = basis weight of the ith web region (g/cm^2)

d_{i+1}, d_i = distance to targets above and below ith web region, respectively.

Figure 3 is a typical set of displacement data with the applied pressure profile included for reference. Before the "nip" closes and after it opens, the sheet is unrestrained so the signals may not accurately reflect the true positions of the targets in the sheet. However, a method has recently been developed to obtain accurate measurements in the post nip period.

These, as well as other raw, unfiltered displacement data obtained with the sheet under restraint, have proven to be very clean and reproducible.

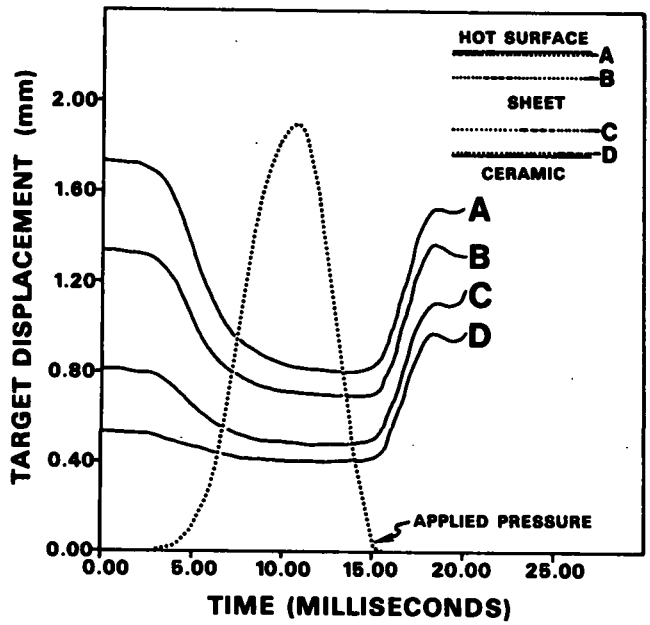

Figure 3. Typical unfiltered recordings of the target displacement histories (A-D) used in the calculation of dynamic density profiles, and the total nip pressure for wet pressing conditions at 20°C. P_{max} = 4.8 MPa.

A number of factors are critical to accurate density determinations. These include proper transducer calibration; target material, thickness, and temperature; target embedding method; basis weight variation; and parallelism between pressing surfaces. To achieve a high degree of accuracy, each of these factors must be addressed.

Under some severe drying conditions, such as impulse drying, the target may increase in temperature up to about 250°C. Since changes in target resistivity and magnetic permeability with temperature are known to result in significant displacement measurement error, a series of experiments was performed to determine how this problem could be reduced or eliminated. Some typical results are plotted in Fig. 4 as measurement deviation (percent deviation from true value) versus target temperature for several thicknesses of nickel and copper mesh. Considering these measurements, it is apparent that increasing target thickness and use of a nonmagnetic material will enhance the thermal stability of the system to the point where the effects can be ignored. Over the range of temperatures used in impulse drying, a 38-μm thick copper mesh material may be used without significant measurement deviation resulting from thermal effects. For wet pressing conditions at constant temperature, target thicknesses as low as 12.5 μm may be effectively used.

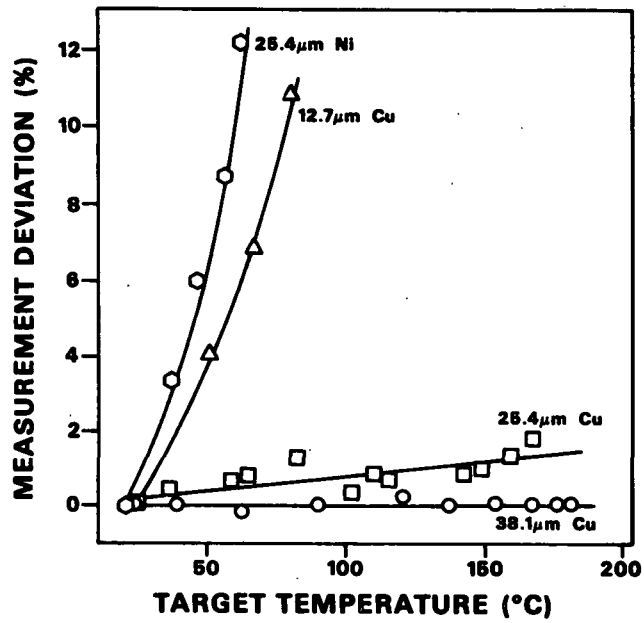

Figure 4. Displacement measurement deviation (percent deviation from the true value) as a function of target temperature for various thicknesses of copper and nickel mesh.

While increasing target thickness improves the thermal stability of the measurement, it increases the amount of fiber network disturbance associated with the target's presence. To minimize this problem, the ratio of target to sheet thickness must be kept small. It is also essential that the target be embedded in the sheet in a manner which minimizes fiber network disturbance. A method to accomplish this will be described later in this paper.

The openness of the target should also be large enough to minimize flow resistance and interfacial effects. The open area of the copper mesh used in experiments to date has varied between 65 and 75%, depending on target thickness.

An error analysis showed that the degree of parallelism between pressing surfaces is the largest potential source of error in the density profile measurement. This error may vary over a wide range, depending on the severity of misalignment. In order to achieve an acceptable degree of parallelism, a number of corrective measures had to be taken. The press heads had to be machined and surface-ground as flat and parallel as possible. The pressing apparatus had to be designed and constructed to ensure parallel contact of the press surfaces. For the falling weight simulator, this required proper alignment of guidance shafts, close tolerance bearings, and balancing of the falling head.

Fine adjustment of the press surface level was accomplished in most cases by shimming but was also controlled by adjustment screws (not shown in Fig. 1) which were used to control the amount of compression on the rubber pad that was sometimes included in the lower head. The four displacement transducers were used to track the displacement of the pressing head to determine if parallel contact was being made dynamically. If not, then adjustments were made accordingly. Nip impressions were also performed to determine uniformity of pressure application.

In preliminary experiments, it became apparent that the manner in which targets were embedded in the sheet significantly affected the density determination. Placing the targets between previously formed fiber layers that had been pressed together yielded displacement histories which were not realistic or repeatable. A handsheet forming method was then developed in which the targets were embedded in the sheet during formation. This greatly improved the density profile measurement. Apparently, when layered handsheets with targets between layers are used, the targets disturb the fiber network and result in local areas of increased thickness. In contrast, when the target is embedded during formation, fibers are displaced by the target and layer interfaces are eliminated, resulting in a more uniform structure. This concept is illustrated in Fig. 5.

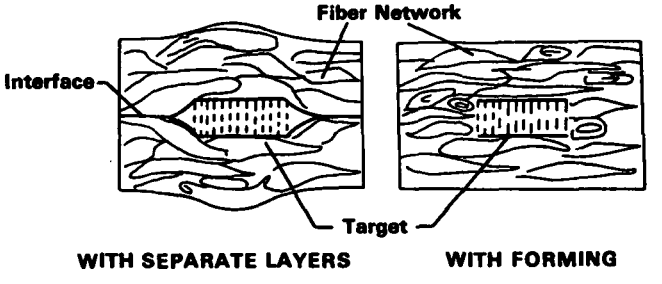

Figure 5. Comparison of two types of target placement; placing target between previously formed fiber layers and placing target in the sheet during formation.

Handsheet Preparation

A constant rate forming apparatus, similar to that described by Cowan (9) is used to form handsheets with uniform and reproducible fiber structures. Experiments have shown the basis weight variability within paper samples to be relatively small, with a coefficient of variation of 0.94%.

Handsheet formation is initiated by the combined flow of fiber slurry at a consistency of 0.01% and distilled water into a 14-cm diameter forming tube. After a predetermined amount of fiber has entered the tube, fiber flow is stopped and the flow of distilled water is increased to maintain a constant total flow rate. All fibers are allowed to settle, and then, in the presence of a continuous flow of distilled water, a target is positioned on the fiber mat surface. Positioning is accomplished with a specially designed insertion tool which allows the target to be deposited on the mat surface without disturbing the fibers or interrupting flow. These steps are repeated until all targets are embedded. This method produces uniform handsheets without the interfaces that develop when separate fiber mats are conjoined. After formation, the handsheets are lightly pressed between blotters to a target moisture content, stored overnight, and tested the following day. Long term storage is not recommended, as oxidation of the target material can result in displacement measurement error.

WET PRESSING RESULTS

Measurement of the z-direction density profile development offers a unique tool for investigating the dynamics of wet pressing. By observing the response of the sheet structure within the nip, much can be inferred about wet pressing fundamentals. Figure 6 shows density measurements for each of three sheet thickness regions taken over a typical wet pressing event (also see Fig. 1). The 170 g/sq m handsheet, adjusted to a moisture ratio of 6.33 prior to pressing, was made from a 735 CSF, fines-free, softwood kraft furnish.

The initial compression of the sheet compares well with the nonuniform density development predicted by MacGregor (5). Since the sheet is initially saturated, pressurization of the liquid water begins immediately. The hydraulic pressure gradient required for fluid flow develops first in the flow exiting region 3. Consequently, this region densifies first. As the compression continues, the hydraulic pressure gradient increases in magnitude toward the press surface. Thus, the middle region densifies next, followed by the press surface region. The degrees to which the regions densify during this time depend on the hydraulic pressure drop across each region which develops in response to the flow resistance of the fiber network. Since flow from the press surface region encounters the greatest cumulative flow resistance, and the flow exiting region the least, it follows that the flow exiting region densifies at the highest rate, followed by the middle and press surface regions, respectively.

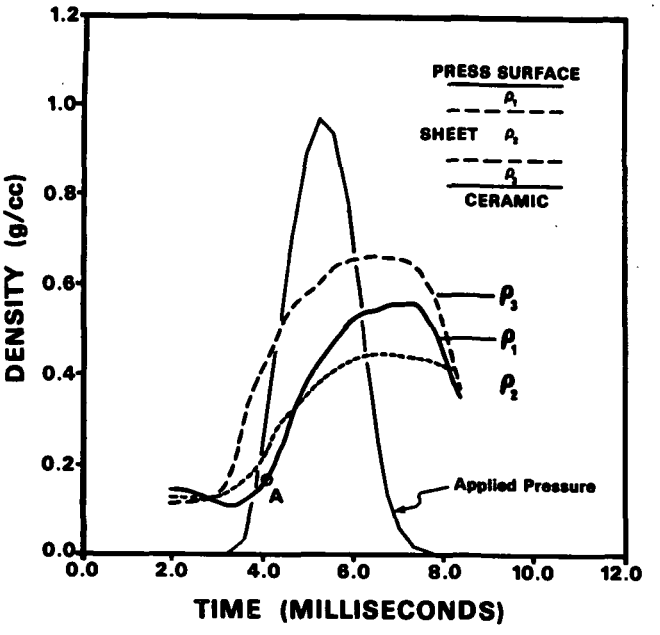

Figure 6. Density-time relationships for each of three sheet thickness regions taken over a single wet pressing event. Basis weight = 170 g/m^2, incoming moisture ratio = 6.33, freeness = 735 CSF, P_{max} = 6.5 MPa.

Since the sheet in Fig. 6 was initially of a very high moisture, it crushed in the nip. The density profile measurement offered an unusual view of the crushing phenomenon. The abrupt change in slope of the press surface region (point A) is believed to signal the onset of crush. It appears that the rapid increase in density of the flow exiting region led to a large hydraulic pressure in the press surface region which could not be reduced through the transverse flow of water from the sheet. Thus, the liquid flow followed the path of least resistance, resulting in the lateral flow of water in the press surface region. The density of the region at point A (0.17 g/cc) suggests that a cohesive fiber network had yet to develop which could resist the shear forces arising from the lateral water flow. Consequently, crushing occurred in this region through disruption of the fiber network by fluid shear forces. The rapid increase in the measured density of the press surface region is an artifact of crushing that results from the radial flow of both water and fiber out of the press nip. It should be noted that the crushing that occurred in the press surface region, as indicated by Fig. 6, could also be verified by visual examination of the crushed sheet.

While the results of the density profile measurement presented above could have been predicted qualitatively by current wet pressing theory, these new measurements provide the first direct experimental verification of the density profile development described by MacGregor (5) as well as detailed quantitative information useful in process modeling. Never before has the onset of the crushing phenomenon been observed in the nip. The Institute of Paper Chemistry is utilizing this technique for further investigation into various aspects of the wet pressing process. These include evaluation of new consolidation processes, studies of dynamic compression/expansion behavior of fiber webs, rewetting, post nip expansion, and process modeling.

IMPULSE DRYING RESULTS

As stated earlier, this measurement technique was originally developed for study of density development during impulse drying. Impulse drying, which combines elements of wet pressing and hot surface drying, refers to water removal from a high temperature press nip. The process includes dewatering and densifying forces which result in high average sheet density values as well as nonuniform z-direction density profiles. This drying regime is typically bounded by nip temperatures of 150-500°C, pressures between 0.3-7.0 MPa, and residence times up to 100 milliseconds. Sprague (10) has demonstrated extremely high dewatering rates and significantly lower specific energy use compared to conventional drying. Property improvement, strongly influenced by density development, is another attraction of this process.

Development of the measurement technique was, in part, prompted by the need to better understand the relationship between property improvement and densification. The density profile measurements have, however, considerably increased our understanding of the dynamic physical processes which occur during impulse drying. Figure 7 shows density measurements over a typical impulse drying event for a 173 g/m^2 handsheet, originally at a moisture ratio of 1.4, impulse dried at 315°C.

Initially, the sheet densifies uniformly under mechanical compressive forces as it would during wet pressing. Since it is at a low moisture ratio, there is little fluid resistance to compression to cause an uneven density profile. Near the calculated point of sheet saturation (0.48 g/cc), the densities of individual regions begin to develop to different magnitudes, producing nonuniform density development similar to that observed in Fig. 6 for wet pressing.

The lower regions, which continue to densify beyond the saturation point, reach a maximum

density near the peak applied pressure and then begin to expand. The density of the hot surface region, in contrast, levels out to a near constant value over the central part of the nip. Pressurization of the fiber structure, as indicated by vapor pressure measurements at the hot surface, resists further densification by the externally applied pressure.

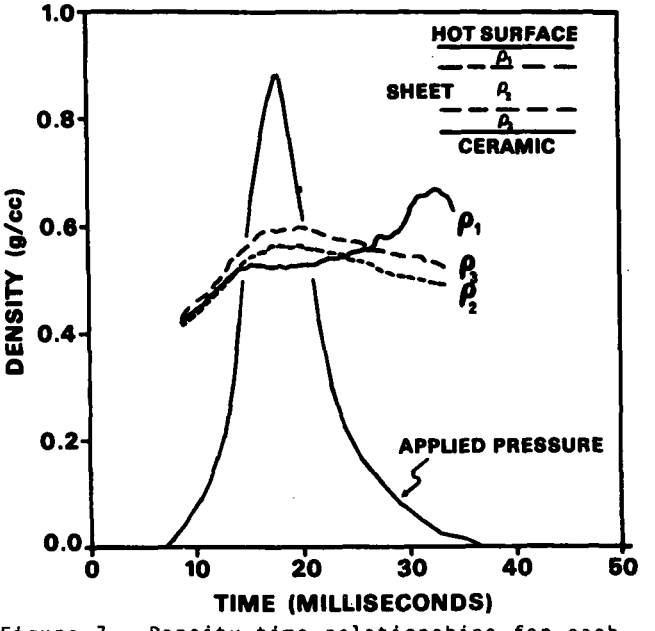

Figure 7. Density-time relationships for each of three sheet thickness regions taken over a single impulse drying event. Basis weight = 173 g/m^2, incoming moisture ratio = 1.4, freeness = 735 CSF, P_{max} = 4.14 MPa, temperature = 315 C.

As the applied pressure is reduced, the hot surface region rapidly densifies. During this time, the vapor pressure drops with the applied pressure and results in the collapse and densification of the previously vapor-filled structure. The mechanisms responsible for the density development observed during impulse drying were treated in more detail in an earlier paper (6).

The intense dewatering and densifying forces of impulse drying result in high average sheet densities and nonuniform z-direction density profiles. Measurements of the density distribution of impulse dried sheets by other means, such as sheet grinding and scanning electron microscopy (11), demonstrate that much of the density profile developed dynamically is retained in the fully dry sheet.

The measurement technique described in this paper represents the first quantitative measurements of the development of a z-direction density profile in a dynamic press nip. These measurements have facilitated a more complete understanding of the dynamic physical processes of impulse drying and have clarified key dewatering and densifying mechanisms.

SUMMARY

A new method for investigating consolidation processes has been presented, in which the instantaneous z-direction density profile is measured while the sheet is in the nip. The measurement system is relatively simple to develop, although much care must be taken to reduce the potential sources of measurement error which may result from improper equipment design or unsatisfactory sheet forming techniques.

The density profile measurement utilizes a pair of press heads which are used on a falling press-nip simulator as well as an electro-hydraulic testing system. The movement of targets, which are embedded in the sheet at various levels, is tracked during compression by four displacement transducers mounted in the lower head. Thicknesses of three regions of known basis weight are determined from adjacent target separations and the apparent density profile is calculated directly.

To obtain a good density profile measurement, several factors are of critical importance. These include proper transducer calibration; target material, thickness, and temperature; target embedding method; basis weight variation; and parallelism between pressing surfaces. These factors have been discussed and a sheet preparation method described which has been shown to be essential to successful density measurements.

Some limited results have been presented which demonstrate the applicability of the density profile measurement. For wet pressing, the predicted nonuniform density profile development described by MacGregor (5) was verified and the phenomenon of crushing was briefly examined. For impulse drying, measurements of the unusual density development were described.

The density profile determination has aided and continues to aid in the wet pressing and impulse drying research at The Institute of Paper Chemistry. It should be emphasized that this novel technique may be useful in the investigation of other consolidation processes and related phenomena. Studies of dynamic compression/expansion behavior, crushing, rewetting, post nip expansion, and data collection are examples of some of the areas under consideration at The Institute of Paper Chemistry.

ACKNOWLEDGMENTS

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